A PULSE POSITION MODULATED LASER COMMUNICATIONS SYSTEM

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Monterey, California

THESIS

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LASER COMMUNICATIONS SYSTEM

by

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A Pulse Position Modulated

Laser Communications System

by

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ABSTRACT

An optical communications system, suitable for simplex voice transmission is constructed, and demonstrated for straight line-of-sight, and for curved path operation using lenses and fiber optics. The system uses a pulsed gallium arsenide injection laser in the transmitter, operating at repetition frequency eight to fifteen kilohertz, and a p-i-n photodiode in the receiver. Pulse position modulation is used to transfer information as well as to trigger an avalanche transistor switch to drive the laser.

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ACKNOWLEDGEMENTS

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I. INTRODUCTION

A. BACKGROUND

The laser is a source of intense, directional, and coherent radiation. At optical wavelengths (10^{13} to 10^{15} HZ), the bandwidth of a single laser beam can carry all the television programs in this country [Ref. 1]. Lasers can have minimum beam divergences on the order of milliradians with virtually no side lobes. This insures directionality, security, and no cross talk or interference from adjacent beams or even from lower frequency carriers. Terminal equipment takes up only small amounts of space making extremely large high gain antennas unnecessary. Power needed for conventional omnidirectional antennas is not needed for channeling the narrow laser beam.

The laser would then seem well suited for communications purposes; however, there are disadvantages that accompany the advantages. Lasers are very inefficient--most having efficiencies of less than one percent for conversion of input power to optical power. For transmission paths through the atmosphere, light is easily scattered by clouds, smog, rain, etc. Transmission by light pipes is often accompanied by attenuation losses [Ref. 2].

Nevertheless, an optical communication system operates in a similar manner to a conventional system, and may be studied in a similar way. Figure 1 shows a generalized optical communications system.

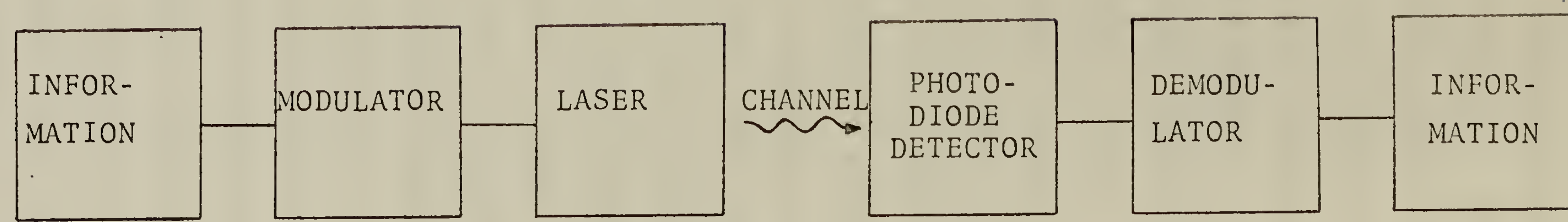


Figure 1: Laser Communications System

Experiments have been conducted with nearly every type of laser for use in optical communications systems. Some of the most interesting tests have been conducted with the gallium arsenide (GaAs) injection laser. Since its discovery in 1962, the GaAs laser has been found to exhibit intensive radiance, and narrow spectral lines, plus it has been found that semiconductor lasers have the highest energy conversion of any laser. This would then seem ideal for use in a communications system. However, because of the small size of the GaAs crystals, these lasers produce small power output. Also, the high current pulses needed to produce laser emissions cannot have repetition frequencies in excess of several kilohertz without requiring cryogenic cooling--a severe limitation in voice communications [Ref. 3].

There are many and varied ways of modulating a laser just as there are for other carrier waves, and the type of laser will limit the type of modulation scheme used. In the case of semiconductor lasers like GaAs, modulation is possible using amplitude, frequency, and pulse modulation; however, experiments have shown that pulse modulation is the most feasible and easiest to implement [Ref. 4].

Perhaps the greatest difficulty encountered in laser communications is the transmission channel. Rain, clouds, smog, and even birds can make atmospheric transmission of a laser ineffective. A better method for some applications is the light pipe. Mirrors and lenses can be placed in a conduit to channel and focus a laser beam. A pipe containing

a gas lens can also be used to channel a laser with little or no attenuation. Still another method of light conduction is the fiber-optic guide. Here the use of lenses and mirrors, and all form of solid reflector is avoided by using a tiny strand of fiberglass whose diameter approaches light wavelengths. The fiber can then function in a similar manner to a microwave waveguide, and transmit in a continuous curved path. There is little or no optical frequency interference between adjacent fibers, and the tiny fiber strands are difficult to tap giving relative transmission security. Commercial grade fibers have the disadvantage of relatively high attenuation. Research continues for the development of a suitable low-loss fiber.

Once a laser signal is transmitted through the channel, detection is a simple matter. Detectors have been developed which display a strong response to incident optical signals, and sufficient instantaneous bandwidth to accommodate the information bandwidth of the incoming signals. They also contribute very little noise to the system [Ref. 5]. Incident light on the photodiode causes a weak photocurrent to flow which can be amplified and demodulated to reproduce impressed information. The p-i-n diode is especially responsive to near infrared radiation making it well suited for use in GaAs laser systems.

Commercial laser communications systems began to appear on the open market around 1970. Two such systems of particular interest were developed by Santa Barbara Research

Corporation [Ref. 6] and by Holobeam, Inc. [Ref. 7]. Both systems make use of the laser properties of GaAs in frequency-modulated semi-secure, directional, short-range walkie-talkies. A third system presently under development at the Navy Electronics Laboratory makes use of the light emitting diode properties of GaAs in a pulse-position modulated telephone circuit. The much higher pulse rates (MHz) possible with LED's lead to better voice transmission and even to multiplexing [Ref. 8].

B. OBJECTIVES

The primary objective of this work was to design, build, and test an optical communications system suitable for simplex voice transmission using a pulsed GaAs laser diode in the transmitter and a photodiode in the receiver. An operational bandwidth of two kilohertz was required to properly represent an intelligible voice signal. The system was to have the versatility of straight line-of-sight communication using lenses as well as non line-of-sight communications using fiber optics. There were no requirements as to power output--only that the system be demonstrated effectively in both above modes. The system was to be used as a laboratory demonstration model of a semiconductor laser communications system with due regard to ease of dismantling and access to various test points.

A secondary objective was compactness in size with the possibility of use as portable equipment. Such a system

might possibly be of interest to the Navy for short-range external or even internal communications aboard ship.

II. DETAILED SYSTEM DESCRIPTION

A. TRANSMITTER

The transmitter consists of three basic parts: the laser diode, the diode pulser circuit, and the pulse position modulation/pulser trigger circuit; see Fig. 2.

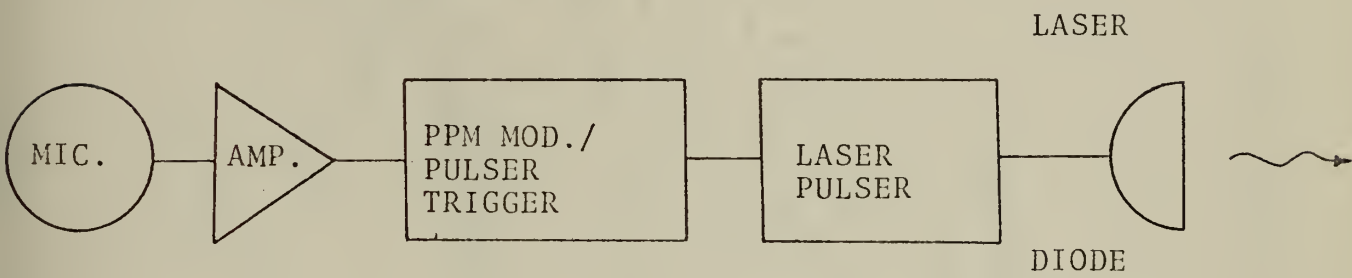


Figure 2: Transmitter Schematic

1. Laser Diode

The source of laser light for the carrier beam is a heterostructure gallium arsenide injection laser diode consisting of n-type GaAs, p-type GaAs, and p-type GaAlAs. See Fig. 3 [Ref. 9].

The passage of current through any semiconductor is caused by the motion of holes and electrons placed in the material by doping. In GaAs crystals, tellurium is used to produce electrons in the n-type material, and zinc is used to produce holes in the p-type material [Ref. 10]. Along the p-n junction in any semiconductor, the holes and electrons recombine to produce radiation of a specific

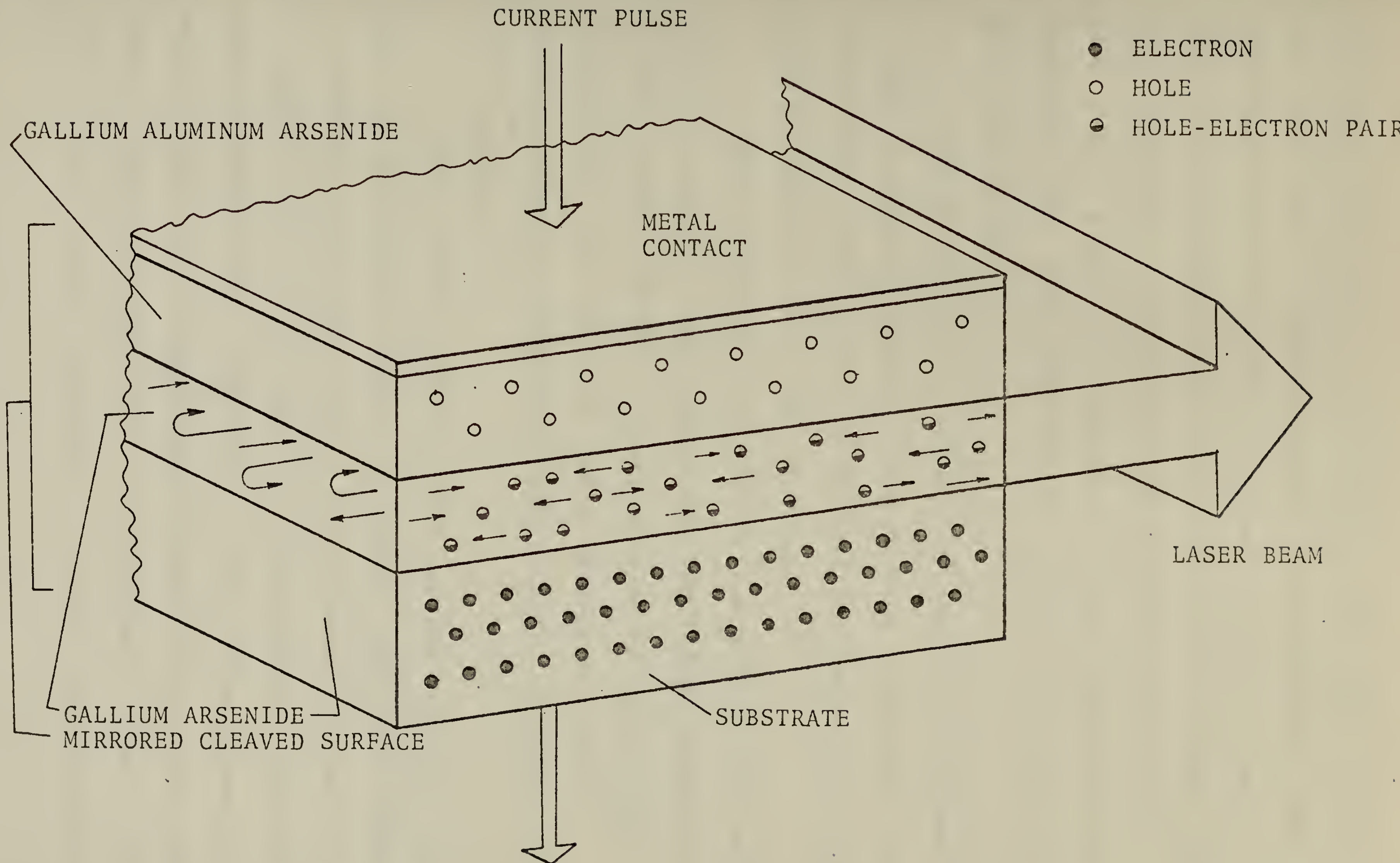


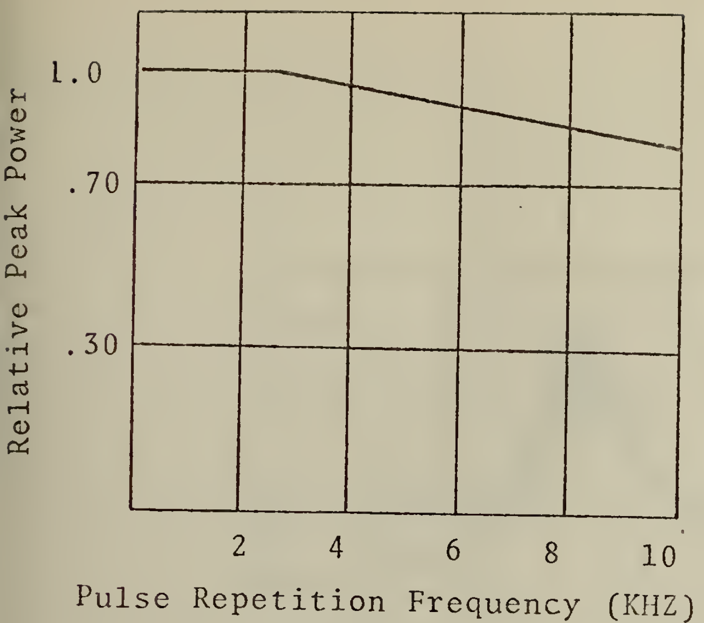
Figure 3: Gallium Arsenide Laser

wavelength depending on the material [Ref. 11]. In GaAs, this radiation is centered around 9050 Angstroms. The interface of the two p-type materials produces a heterojunction--the junction of two crystals with different lattice structures and different energy levels [Ref. 12]. This acts as a barrier to contain the hole-electron recombination within the center cavity, thereby increasing the device efficiency.

The directionality typical of lasers is achieved in GaAs by proper cleavage of the crystal. This will in effect produce the needed end mirrors to channel the stimulated emissions in the right direction.

Three separate laser diodes were used in this work during testing and experimentation--the TA7606 manufactured by RCA, and the LD22 and 23 manufactured by Laser Diode Laboratories. The LD22 was chosen because of the low threshold current required to make it lase. Figure 4 shows LD22 specifications.

Even with the low threshold current required, the diode did not operate exactly as hoped. The laser threshold is achieved in GaAs only when a strong enough current pulse is applied. Up to that point, the diode shows a much wider spectral luminescence (LED mode). The problem encountered with the LD22 was a random jump between LED and laser modes. Figure 5 shows the difference. The problem, caused by the pulser circuit which is covered in the next section, did not



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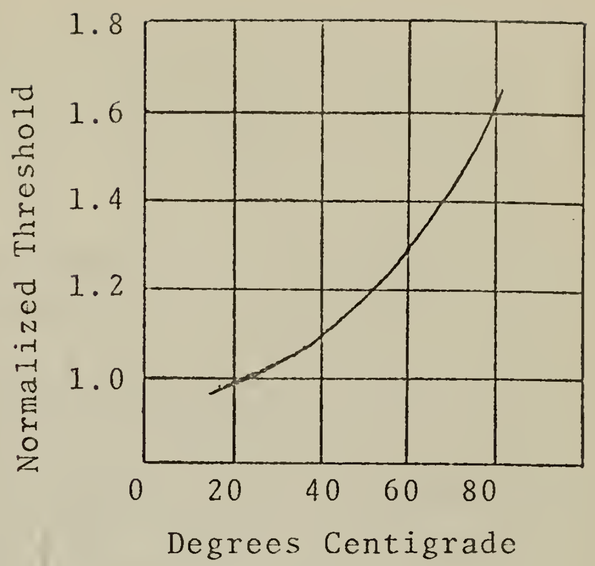

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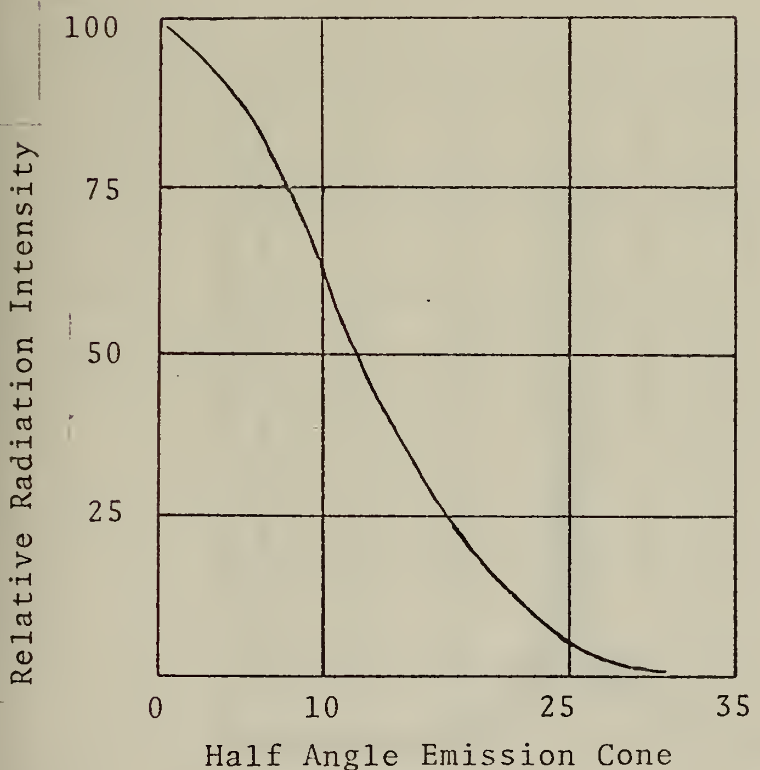
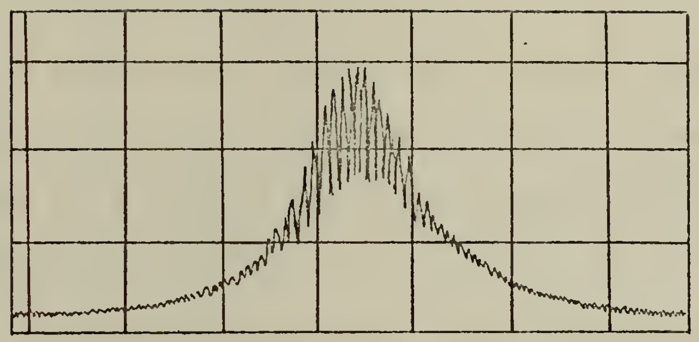
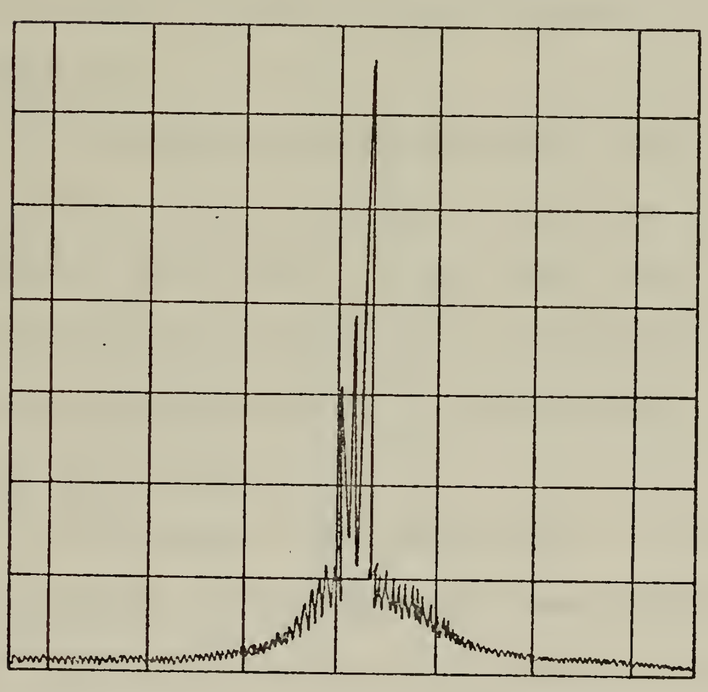


(c)

Figure 4: Operating Characteristics of LD22 (a) Relative Peak Power vs. prf (b) Threshold Current vs. Temperature (c) Angular Dependence on relative radiant intensity



(a)



(b)

Figure 5: Luminescence Characteristics of GaAs (a) LED Mode (b) Laser Mode

affect system performance since the properties of the system are independent of whether the light was coherent or incoherent.

2. Diode Pulser

A pulser was needed which would drive the laser diode strongly enough to make it lase properly, and at the same time be suitable for a pulse-position-modulation communications circuit.

The commercial pulser (LP23 manufactured by Laser Diode Laboratories) was available in the lab. It was compatible with a PPM scheme for external triggering. The LP23 produced one microsecond, 50 amp current pulses with pulse repetition frequency of 1 KHZ. It was thought at first that this prf might be suitable for voice transmission. As seen in Fig. 6, most of the telephone voice is centered around 500 HZ.

A 1 KHZ system would severely limit the fidelity of a voice, but it was felt that it could do the job. Experimenting with this setup, it was found that voice transmission could be achieved; however, it was difficult to filter out the very bothersome hum of a 1 KHZ trigger signal, and still keep any intelligence.

To circumvent this difficulty, a trigger circuit capable of peak current up to 20 amps operating at prf of 10 to 15 KHZ was developed to operate at room temperature [Ref. 14]. By using a capacitance storage circuit along with

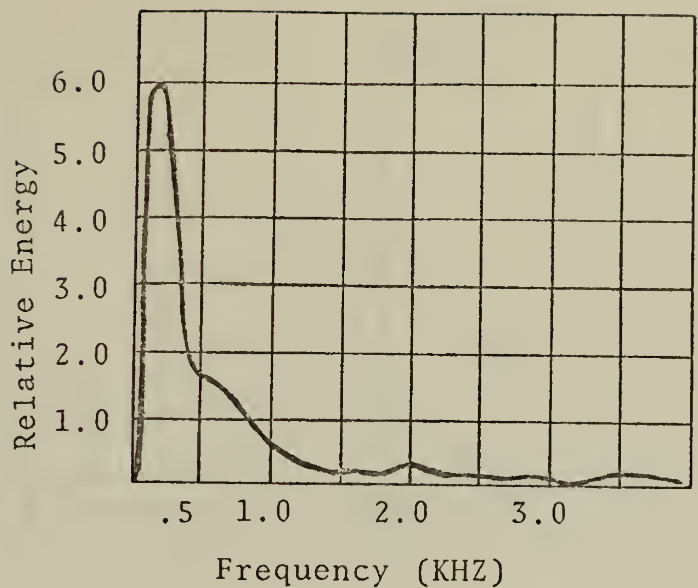


Figure 6: The Telephone Voice, frequency distribution of most talkers [13]

the avalanche-multiplication properties of silicon transistors, this circuit could produce fast rise time (one nanosecond) pulses with peak amplitude sufficient to trigger a laser diode. In order to function properly, a transistor had to be chosen which exhibited a significant difference between the collector-to-base diode breakdown voltage BV_{CBO}, and the avalanche latching voltage LV_{CER}. Figure 7 shows the proper characteristics.

It is desired that the operating point of the transistor circuit be close enough to the avalanche region that a large enough pulse on the base of the transistor would cause the operating point to jump into the negative resistance portion of the curve. This should in turn

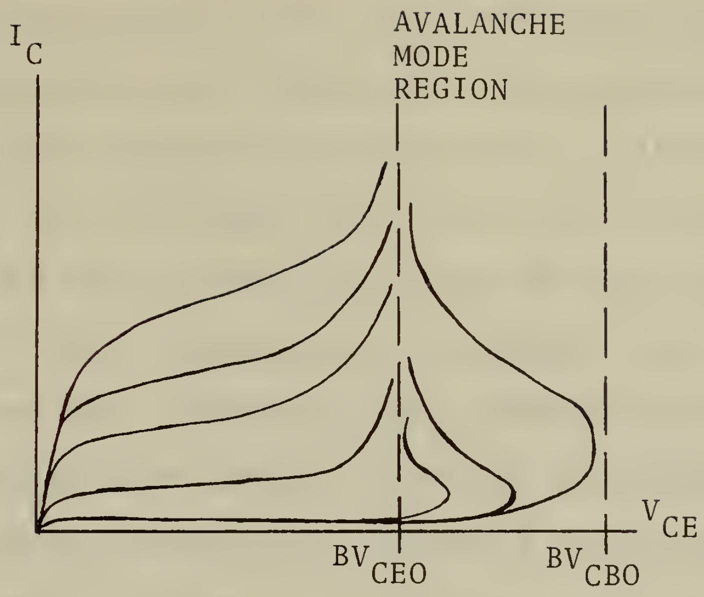


Figure 7: Static Characteristics of an Avalanche Mode Transistor

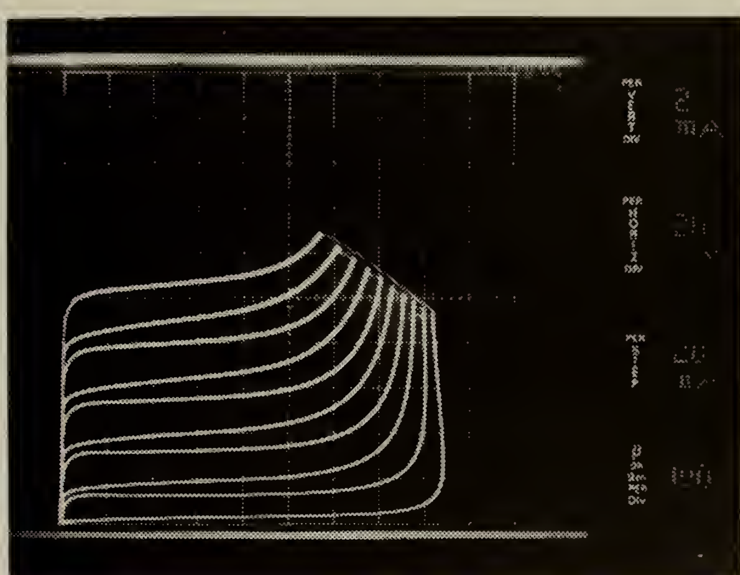


Figure 8: Characteristics of 2N657

cause a large current pulse to be switched through the load. A 2N657 transistor was chosen for the avalanche circuit. Figure 8 shows typical characteristics of this device.

It was found that only one transistor operating as an avalanche switch would not drive the LD22 laser diode. An array of eight transistors was decided on. A circuit was required that would cause all transistors to switch simultaneously even though transistor characteristics vary from one device to another. Figure 9 is the basic circuit design. Each transistor circuit has its own potentiometer and switch in the collector. All potentiometers can be adjusted to produce the exact voltage at each respective collector to cause synchronous avalanche. The summed up current pulses can be picked off a common emitter to drive the diode. The avalanche mechanism is accomplished by a 10 volt trigger applied simultaneously to the base of each transistor.

A printed circuit board was designed and made with two primary design considerations. The first was to design an emitter bus common to all transistors and large enough to handle the peak current required. The second consideration was compactness in size. Figure 10 shows the mask used in the design, and Figure 11 is a photograph of the completed circuit.

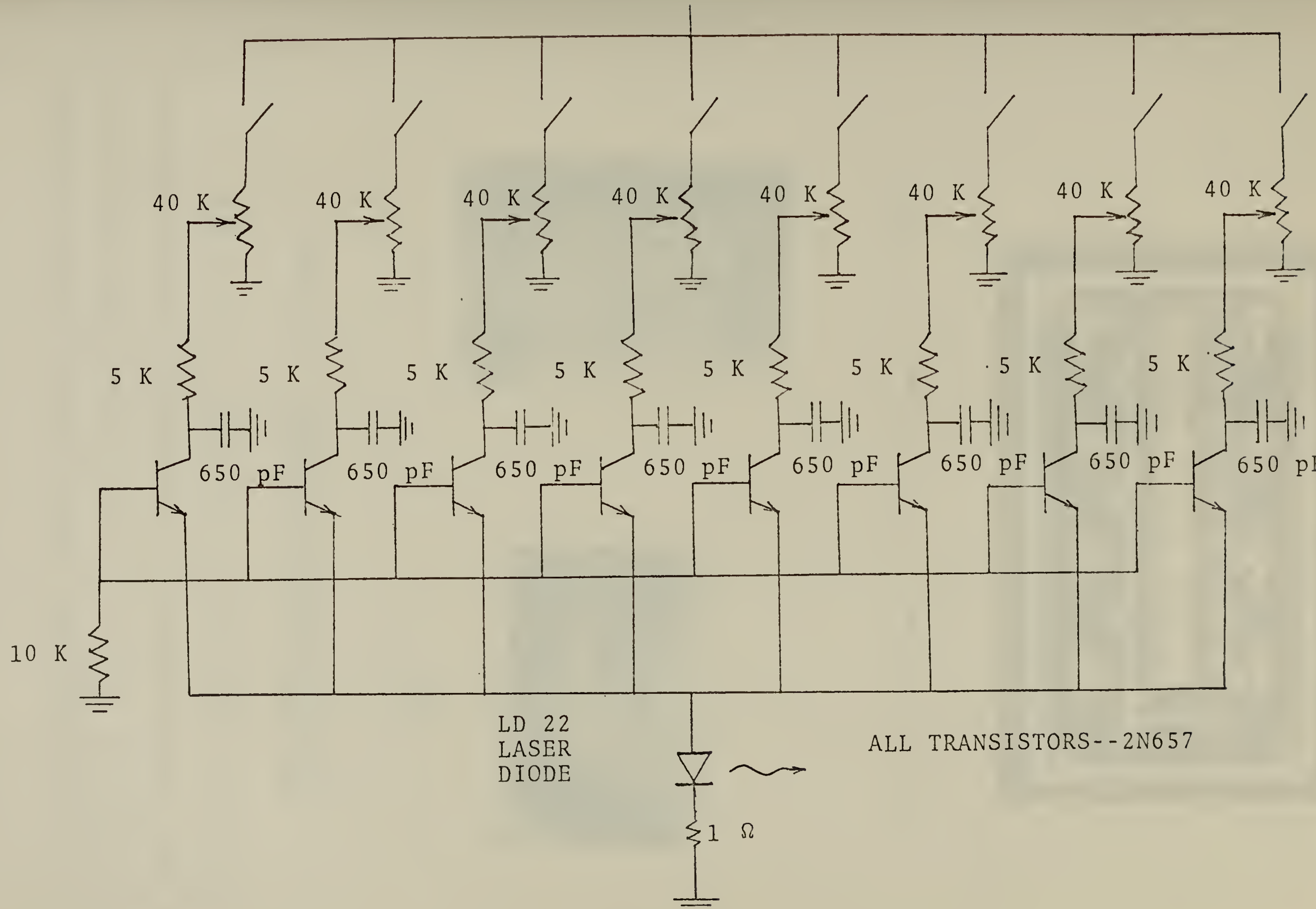


Figure 9: Laser Pulser Circuit

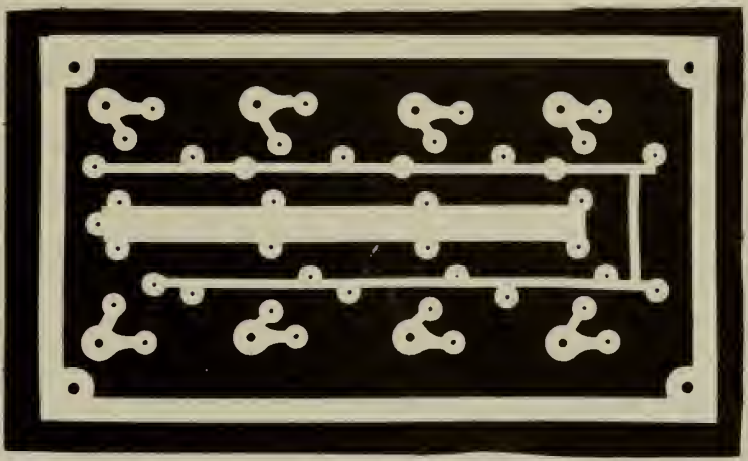
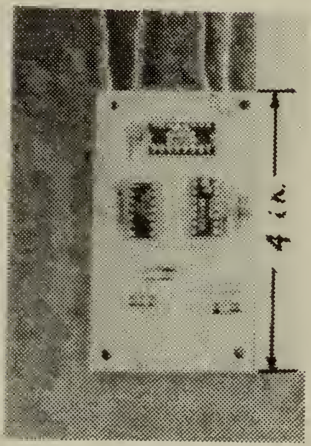
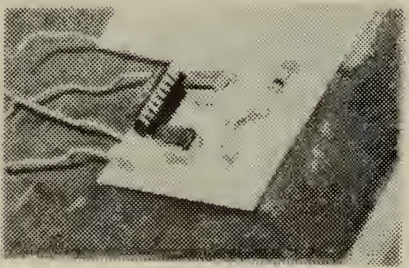


Figure 10: Design Mask for Avalanche Circuit



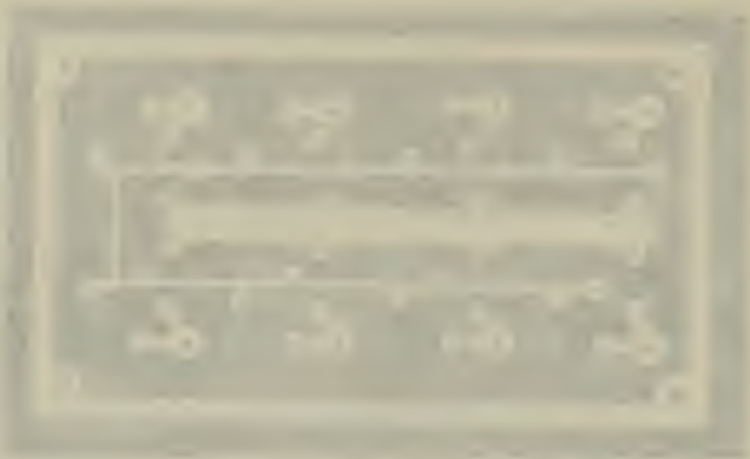
(a)



(b)

Figure 11: Completed Avalanche Circuit
(a) top view; (b) side view

After final construction, the pulser provided the necessary current pulses to drive the GaAs diode. With up to 200 volts supply and at prf of 8-15 KHZ, average current values in excess of 200 milliamps, and peak values of



almost five amps were observed with pulse width 300 nanoseconds. Figure 12 shows the operating characteristics of the pulser circuit.

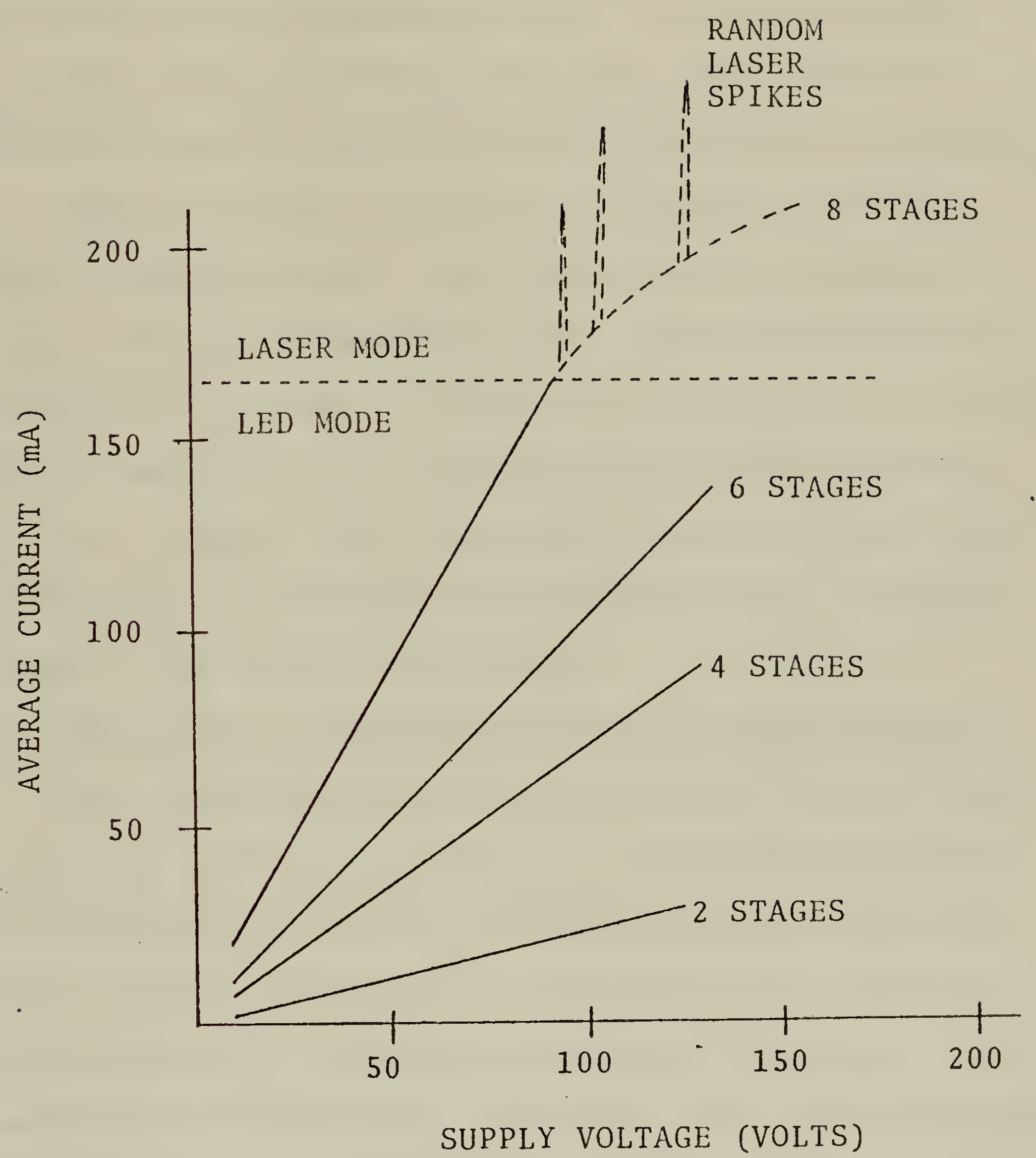


Figure 12: Pulser Characteristics

Since five amps peak current is the threshold to go from LED to laser mode, it was difficult with this pulser to keep the diode lasing. A random switch occurred between laser and LED modes. However, even with the lasing irregularity, the diode displayed a bright luminescence, and was suitable for optical communications. A possible method of avoiding the irregularity of the light output would be selection of transistors with better avalanche characteristics.

Supply voltages in excess of around 150 volts created a heating problem. The transistors and the one-half watt resistors became very hot, and in turn heated up the transmitter housing. Although not detrimental to short periods of testing, it was believed that thermal destruction of this circuit might eventually occur at room temperature. Possible solutions to this problem might be better heat sinks, ventilation, or cooling.

3. <u>Pulse Position Modulation/Pulser Trigger Circuit</u>

The avalanche multiplication pulser will work only if a pulse of sufficient magnitude is applied to the base of all transistors to drive the operating point into the avalanche region. Generating a pulse train to trigger an avalanche pulser is a fairly simple matter; however, a system was needed which would carry information in addition to providing the necessary trigger.

An obvious solution would be some sort of pulse modulation. Of all pulsed systems, pulse-position

modulation (PPM) looked the most promising. In PPM, the amplitude and pulse width remain constant, and only the position of the pulse changes in time according to the input signal. This system is well suited to trigger an avalanche system which requires a constant input pulse for each avalanche. Other pulse systems were examined. Pulse-amplitude modulation was ruled out because the changes in pulse height might produce insufficient height to trigger the pulser. Pulse-duration modulation (PDM) was also ruled out because a narrow pulse was needed, and a PDM pulse might be too wide. Pulse-code modulation would require too high a prf for sufficient system bandwidth.

A simple PPM circuit using only two integrated circuits--a voltage controlled multivibrator (VCM), and a monostable multivibrator (MSM)--was available [Ref. 8]. The VCM puts out a square wave train whose frequency is directly dependent on the input signal. The initial frequency of the device may be controlled by external components. In this system, only the leading edge of the square wave from the VCM is used to trigger the MSM. Since the VCM square wave frequency is increased or decreased, so are the pulses produced by the MSM. If an amplified voice signal is fed into a VCM which in turn triggers a MSM, the pulses are advanced or delayed according to the input voice fluctuations; hence pulse-position modulation occurs.

Figure 13 is a diagram of the modified circuit used in this work. A voice signal was fed into a linear

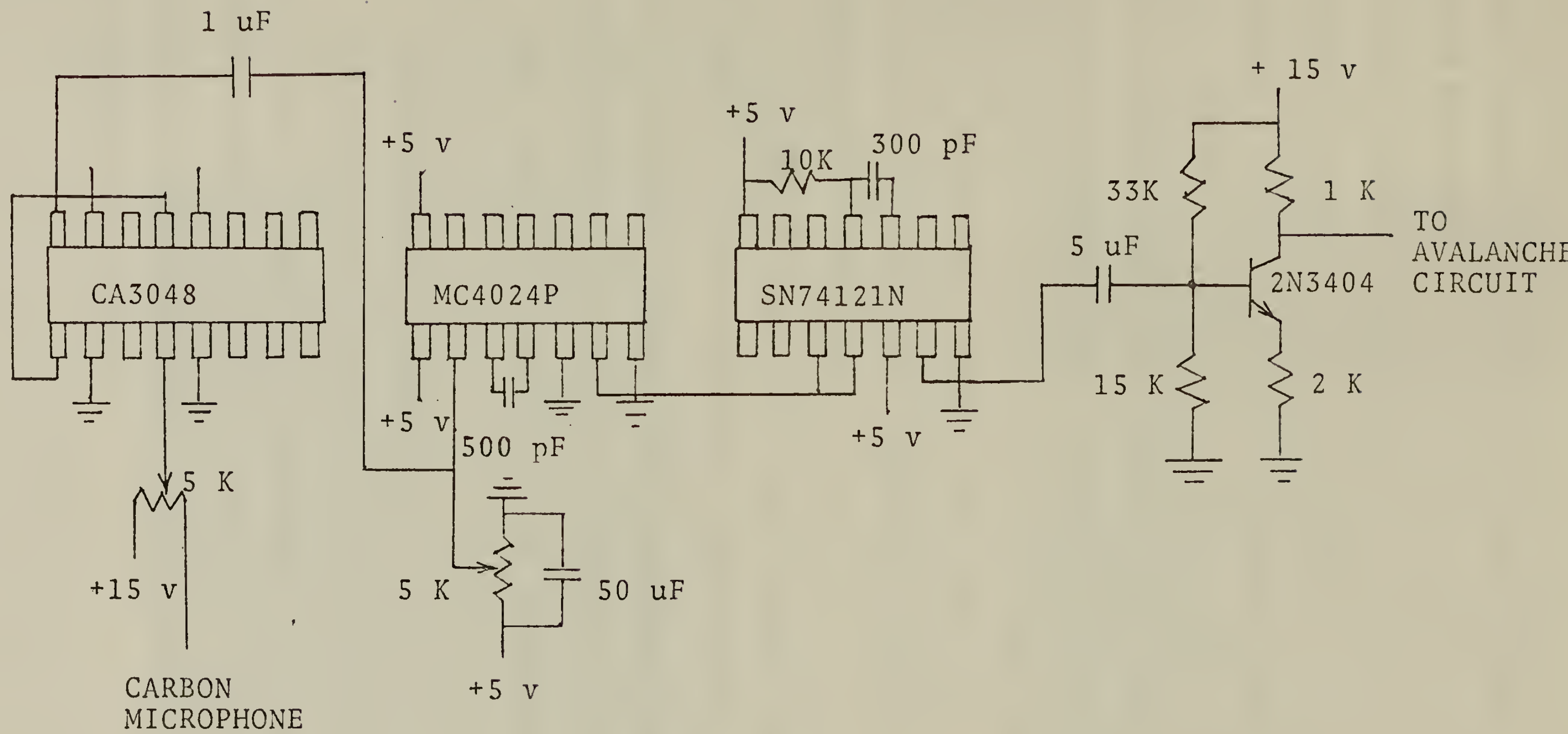


Figure 13: Pulse Position Modulation/Avalanche Trigger Circuit

amplifier (CA3048) which in turn was fed into the voltage controlled multivibrator (MC4024P), and finally into a monostable multivibrator (SN74121N). Also attached to the input of the VCM was a potentiometer to regulate the frequency of the square wave, and eventually the final trigger pulse to a prf of 8-15 KHZ. Since the output of the MSM was not of sufficient amplitude to be a good avalanche trigger, a 2N3404 transistor amplifier was added to boost the pulse to the required height. Figure 14 is the output pulse from the MSM, and Fig. 15 is the final boosted pulse fed into the avalanche trigger. The transistor amplifier did not pass the entire pulse; however, the amplitude and pulse width were sufficient.

A printed circuit board was designed which would contain all the needed components, and still be compatible in size to the pulser board. The two boards would eventually fit together in the casing. Figure 16 shows the mask used to make the board, and Fig. 17 is a photograph of the finished circuit.

4. The Constructed Transmitter

The system had to be packaged and have the capability of being easily dismantled for demonstration purposes. A case was therefore designed to contain all required circuitry, potentiometers, and laser diode. Figure 18 is a photograph of the assembled transmitter.

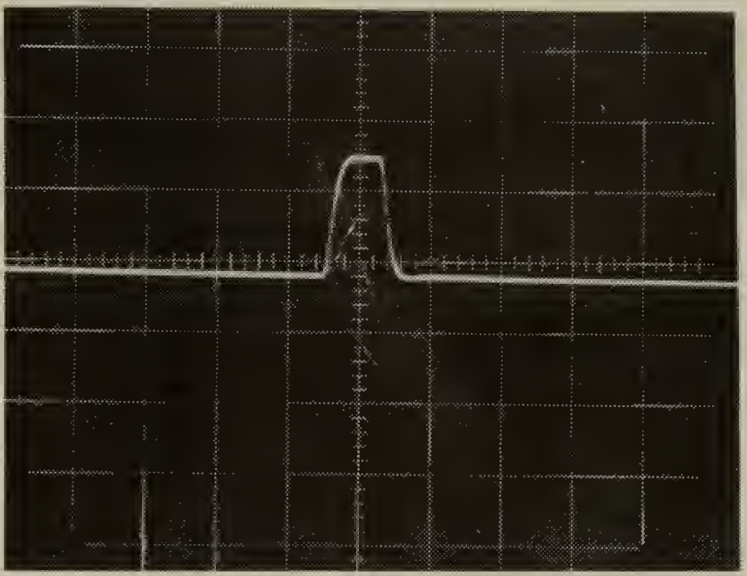


Figure 14: Single Pulse from PPM Circuit.
Horizontal Scale--5 usec/cm
Vertical Scale--1 volt/cm

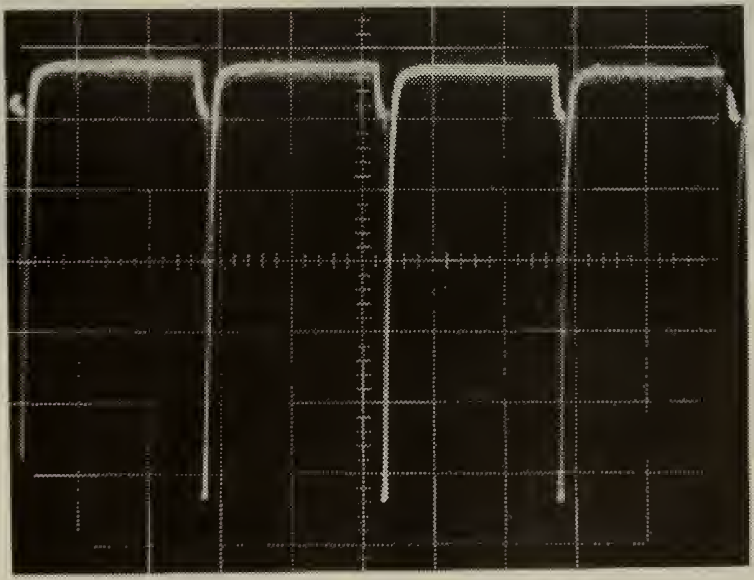


Figure 15: Final Pulse from Booster Circuit.
Horizontal Scale--50 usec/cm
Vertical Scale--1 volt/cm

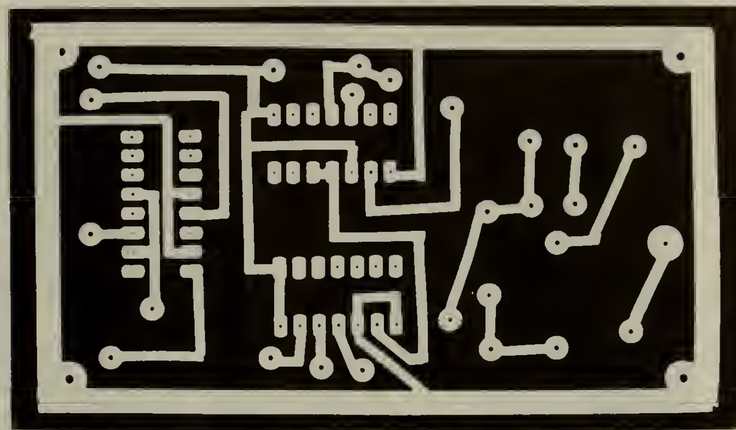
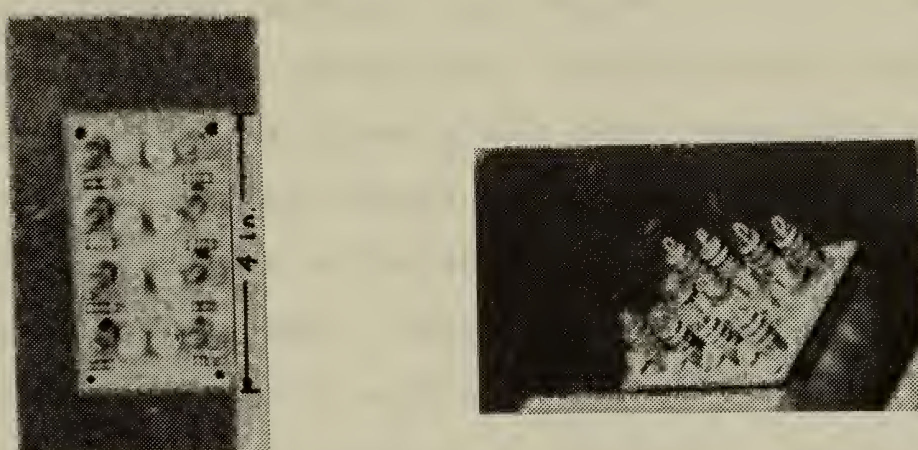


Figure 16: Design Mask for PPM/Trigger Circuit



(a) (b)

Figure 17: Photograph of Completed PPM/Trigger Circuit (a) top view; (b) side view

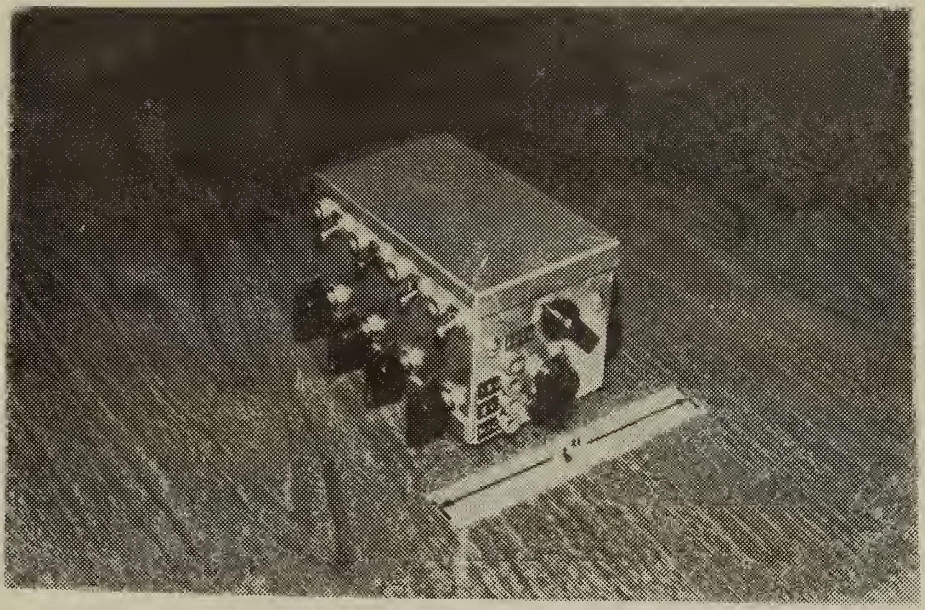


Figure 18: Assembled Transmitter

The sheet aluminum case measures 3 x 3 x 5 inches and stands on four rubber feet. Each transistor has an external on-off switch and a test point receptacle compatible with the standard banana plug, to measure specifically the voltage at each collector, and in general monitor transistor performance. There are also eight potentiometers to regulate voltage to each collector to insure similar operating points and synchronous avalanche. The top of the case is easily slipped off to expose a test point to monitor current pulses through the diode. The end plate has two potentiometers, one to control the audio gain to the microphone and the other to control pulse repetition frequency. Also on the end plates are input jacks for external power supplies, microphone input, and ground connection.

B. RECEIVER

The receiver consists of two basic parts: the photodiode and the photoimpedance converter/final amplifier.

1. Photodiode

A photodiode [Ref. 5] is a square law detector which converts incident light intensity to photocurrent (typically 10^{-8} amps) which can be amplified to usable levels. For this work, a p-i-n photodiode was used because of its sensitivity to incident light of wavelength in the vicinity of .9 microns. Figure 19 is a plot of wavelength vs. quantum efficiency (the number of electrons emitted per incident photon) of a p-i-n diode [Ref. 15].

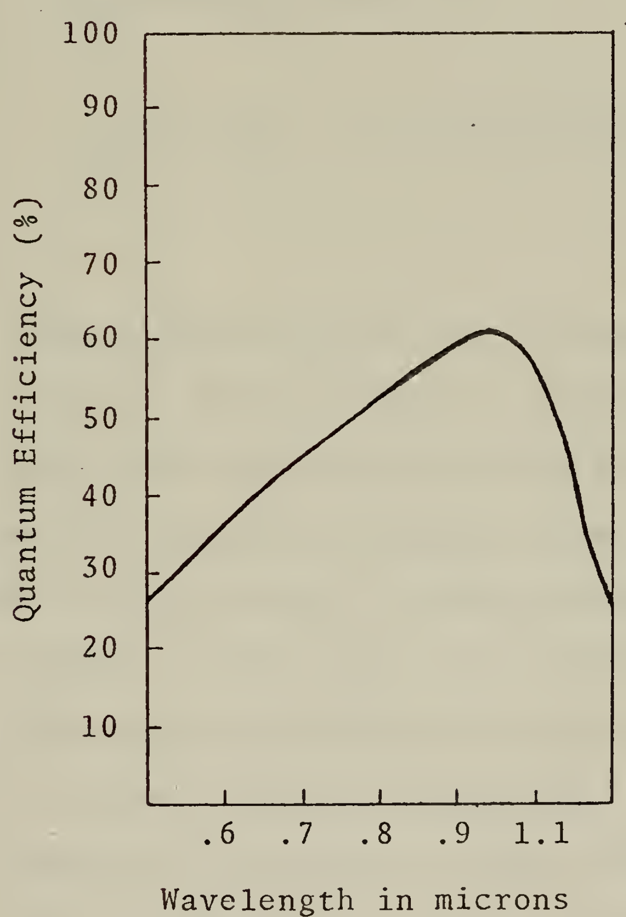


Figure 19: Response of P-I-N Diode

The diode consists first of a SiO_2 coating to pass light, and to protect the diode surface. Surrounding the coating is a metal contact--usually gold because of its opacity to infrared radiation. Beneath that are doped p and n layers separated by an intrinsic i layer; see Fig. 20.

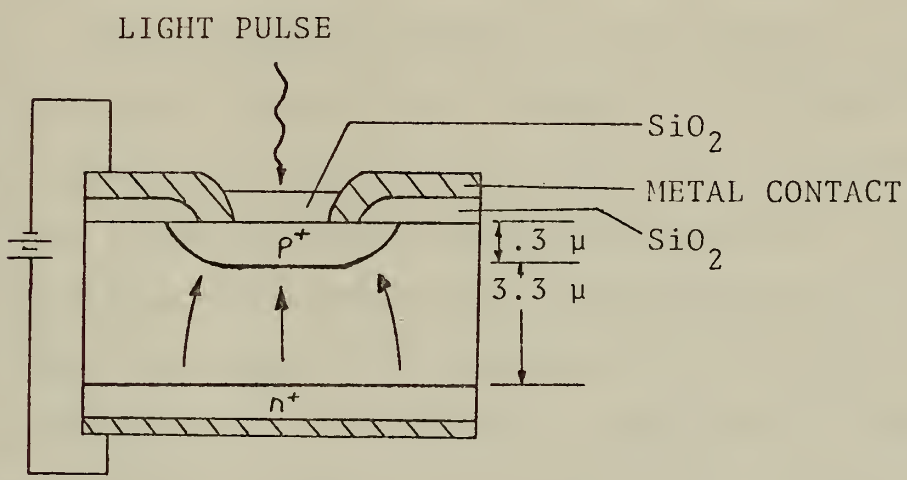


Figure 20: P-I-N Photodiode

Reverse biasing the diode creates an electric field in the i layer. When an incident photon is absorbed into the i layer, hole and electron pairs are created, and then separated by the field to diffuse--electrons to the n layer and holes to the p layer. A photocurrent is made to flow by the creation of the holes and electrons.

The demodulation process takes place in the diode itself. In pulse position modulation, a change in the input signal amplitude will cause a change in the position of a single pulse in time. For a train of pulses, a change in

amplitude will cause a change in instantaneous frequency similar to normal frequency modulation, only with discrete pulses. During any one period of time, higher amplitudes in input signals will cause more pulses to arrive at the photodiode. The response speed of a photodiode is determined by hole and electron transport, and by relaxation processes. For optical frequencies, time constants of processes in the diode are not quick enough to reproduce exact field variations. The RC time constant of the diode also plays a role in the detection/demodulation process. The diode capacitance of approximately two picofarads, and the parallel load resistance of 22 megohms will integrate and hold incoming pulses in the frequency range used. Thus, the photodiode, which responds to intensity, will average over a number of input cycles. The number of pulses arriving in time determines the amount of photocurrent generated by the diode.

For this work, the photodiode reproduced an envelope similar to the input signal, plus a residual train of integrated input pulses within the envelope.

2. Photoimpedance Convertor/Final Amplifier

A p-i-n diode is basically a very high-impedance current generator with no gain. A photoimpedance convertor and preamplifier circuit was available which employs a 2N3819 FET source follower to match the diode's high impedance, and a two-stage transistor amplifier (2N744)

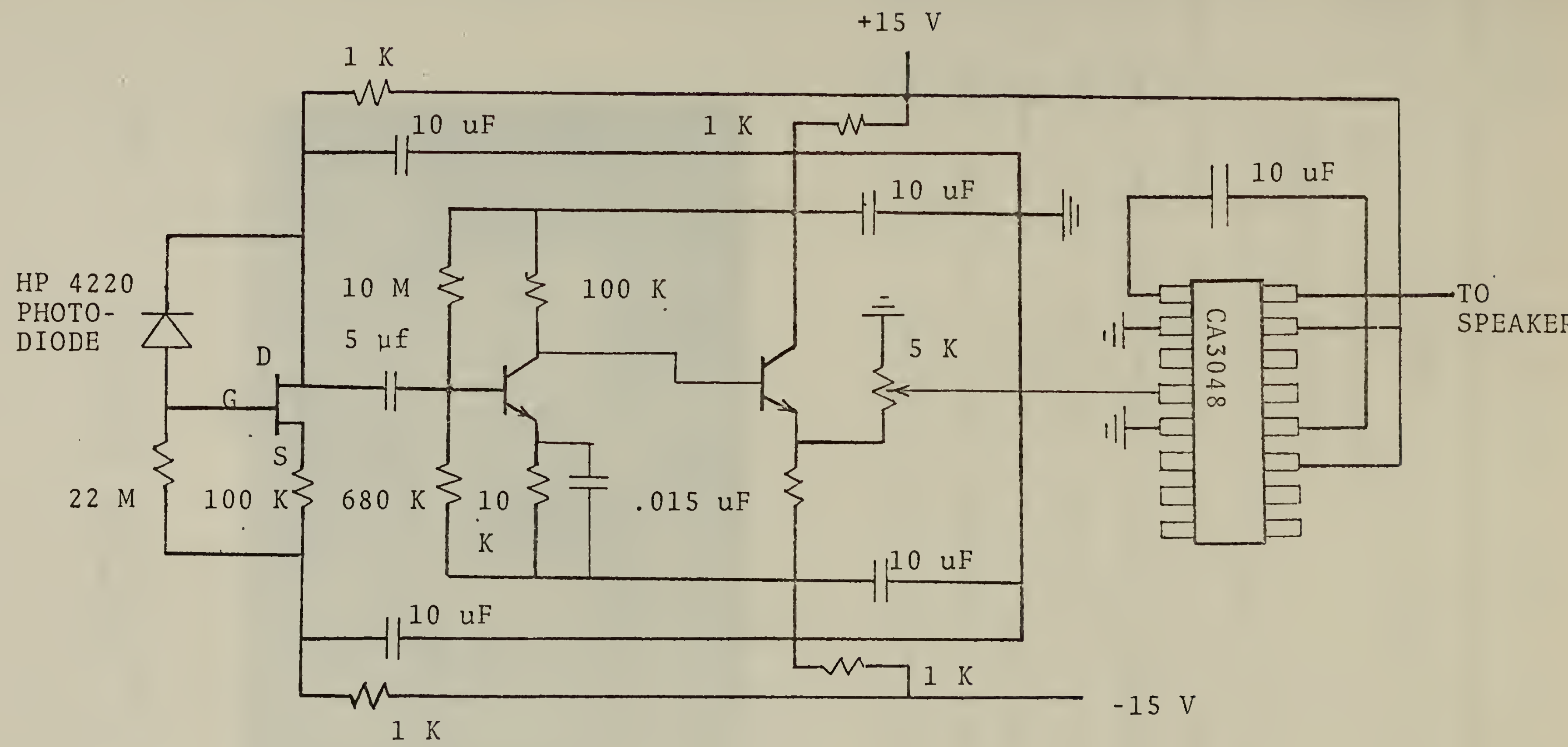


Figure 21: Receiver Circuit

to boost the pulse to observable levels [Ref. 16]. A CA3048 linear amplifier was used as a final amplifier to link directly to a speaker output. Figure 21 is a diagram of the entire receiver circuit.

3. Constructed Receiver

The constructed receiver consists of two printed circuit boards enclosed in a 4" x 4" x 3" aluminum case. External banana plug connections are provided for a ±15 volt power supply and ground connection. An external potentiometer is available to regulate the input signal to the final amplifier to avoid saturation. Figure 22 is a photograph of the transmitter and receiver together.

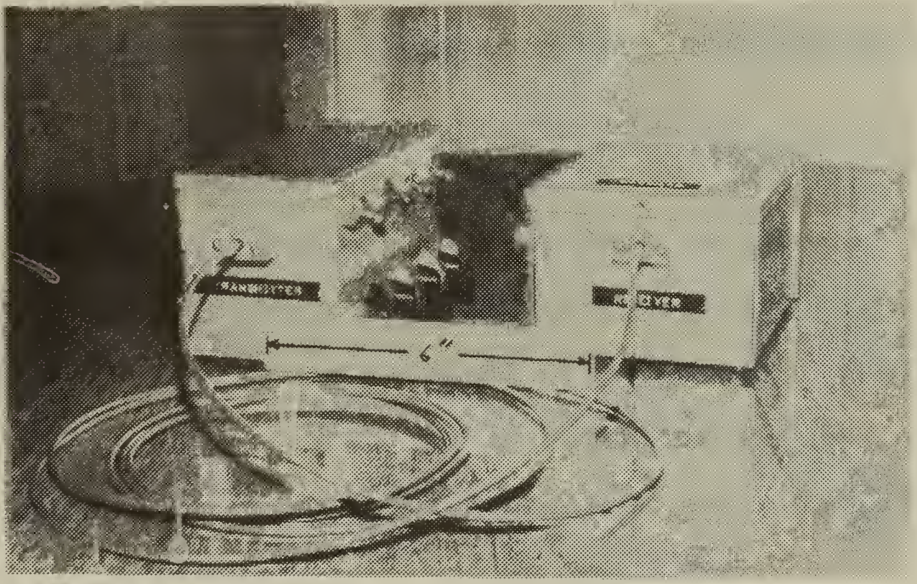
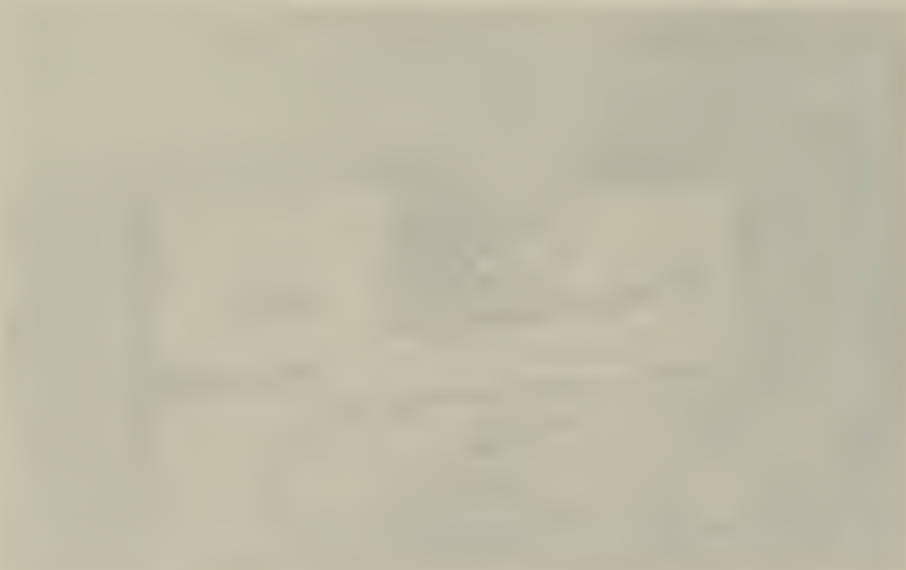


Figure 22: Transmitter and Receiver with Fiber Optic Connected



C. CHANNEL

Two methods were used to channel the pulse from transmitter to receiver: a lens collimator for line-of-sight transmission, and a fiber optic guide for non line-of-sight transmission.

1. Lens

Very little emphasis was placed on line-of-sight transmission, and setting up an elaborate collimator was avoided. The actual collimator used was an eyepiece from a microscope placed on a six-inch tube to correctly position the lens. The tube was attached to the transmitter directly in front of the diode. A great deal of light energy was lost in the tube before collimation. Even so, the lens increased the visual communications distances from 15 to 30 feet. A more elaborate system would have bettered performance.

Although the p-i-n diode used is most sensitive to infrared wavelengths, it does pick up many spurious unwanted transmissions, degrading receiver performance. Placing an infrared filter in front of the receiver cuts out much of the noise. Some light sources (e.g., the sun, and neon lights) are also infrared sources and may only be partially filtered out.

2. Fiber Optic

A far more interesting channel is the fiber optic. For this work, a ten-foot strand of Corning No. 5011 commercial grade fiber was used. Figure 23 shows the

specifications, and Fig. 24 is a drawing of a single fiber in the bundle.

Type	Corning No. 5011
# of Fibers/Bundle	400
Numerical Aperture	.63
n of Core	1.4
n of Cladding	1.63
Acceptance Angle	80 degrees
Core Diameter	50 microns
Loss	1 db/meter

Figure 23: Fiber Optic Characteristics

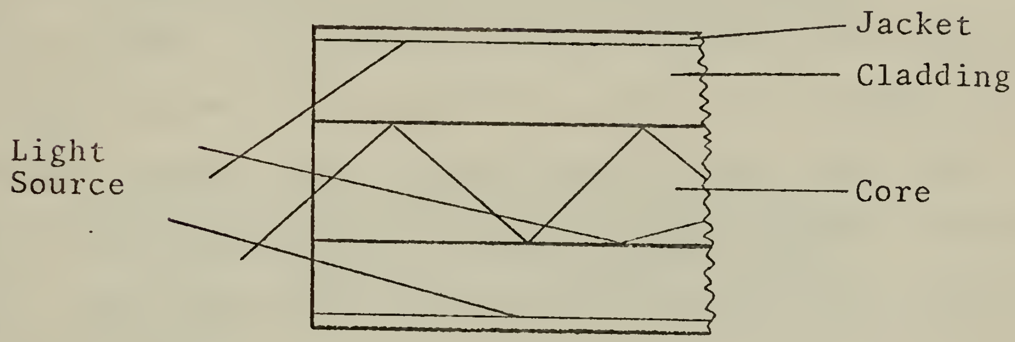


Figure 24: Single Fiber Optic Strand (after [17])

A single fiber optic consists of a fiberglass strand (core) surrounded by another fiberglass strand (cladding) with a higher index of refraction. Light enters the polished end of the core at less than the critical angle for refraction, and is reflected back and forth from wall to wall as it travels along. As the core diameter reaches light wavelengths, the fiber acts similarly to a microwave waveguide.

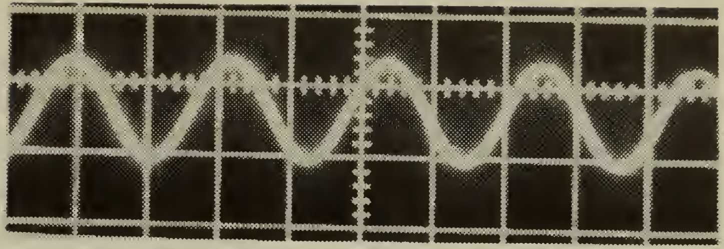
The end of the 400 bundle fiber used for this work was crimped, cut, and polished to allow all light to pass easily. A connection receptable was placed on both transmitter and receiver to allow the fibers to be merely plugged in for a flush connection to the laser and p-i-n diode; Fig. 22.

The fiber optic mode was by far the best means of operation. The acceptance angle of the fiber allowed almost all of the pulsed light to be collected and transmitted to the p-i-n diode. For pulsed operation, losses were negligible. Pulse position modulation does not rely on the height of individual pulses--only the position in time. The high sensitivity of the p-i-n diode, especially to near infrared signals, made operation of the system feasible for even the weakest of pulses.

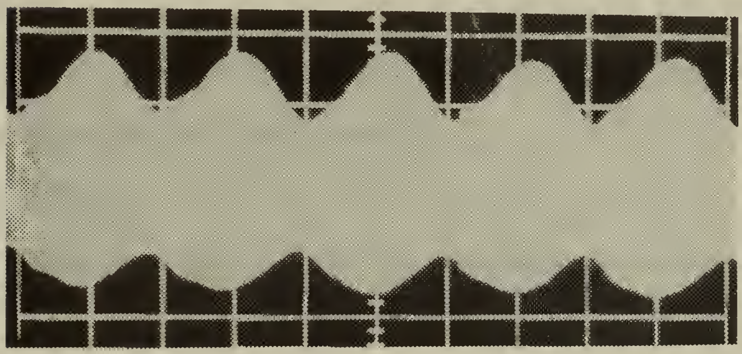
D. COMMUNICATIONS SYSTEM TESTS

A communications system may be tested by checking system bandwidth, signal to noise ratio, transmission loss, and harmonic distoriton. The most important test, although it is not technical is whether or not it works. For communications purposes, this system was to be able to pass an intelligible voice signal of up to two kilohertz.

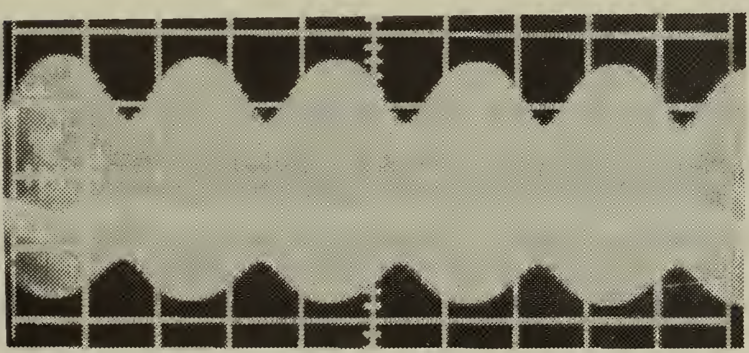
Sinusoidal inputs from 50 to 7000 hertz and were injected into the system. Figure 25 shows the input signal, and the recovered output signals at 100, 1000, and 5000 hertz. The carrier prf was varied from 10 to 15 KHZ with almost no



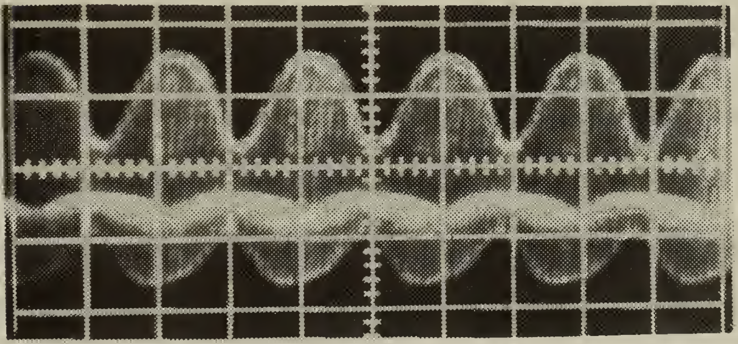
(a)



(b)



(c)



(d)

Figure 25: System Response to Sinusoid (a) Input Signal (b) Output for 100 modulation, 5 msec/cm (c) Output for 1 KHZ modulation, .5 msec/cm (d) Output for 5 KHZ modulation, scale .1 msec/cm Vertical Scale 100 mv/cm

change in signal output. Note that the output contains the input modulation envelope plus the carrier signal. Filtering out the carrier could easily be accomplished by use of an envelope detector; however, it was felt that this was not necessary. The carrier was of too high frequency to be heard by the normal human ear. Only the modulating envelope at the output was heard.

1. Bandwidth

In calculating system bandwidth, it was assumed that each pulse was rectangular, and of pulse width five microseconds, operating at prf of 10 KHZ. The maximum position deviation a single pulse can take with no overlap is the distance between individual pulses less the pulse width of each pulse. For this calculation, that distance was 90 microseconds. The reciprocal of twice that number is a rough estimate of system bandwidth--approximately 5.5 KHZ. This was increased or decreased by the prf control on the transmitter. Figure 26 is a plot of frequency response of the system.

2. Signal-to-Noise Ratio

Signal-to-noise ratio for this system was calculated by measuring the mean output noise power in the presence of a modulating signal, and then measuring the output noise power under noise-free conditions for a sinusoidal input of maximum amplitude. The ratio of these two quantities is the signal-to-noise ratio [Ref. 18].

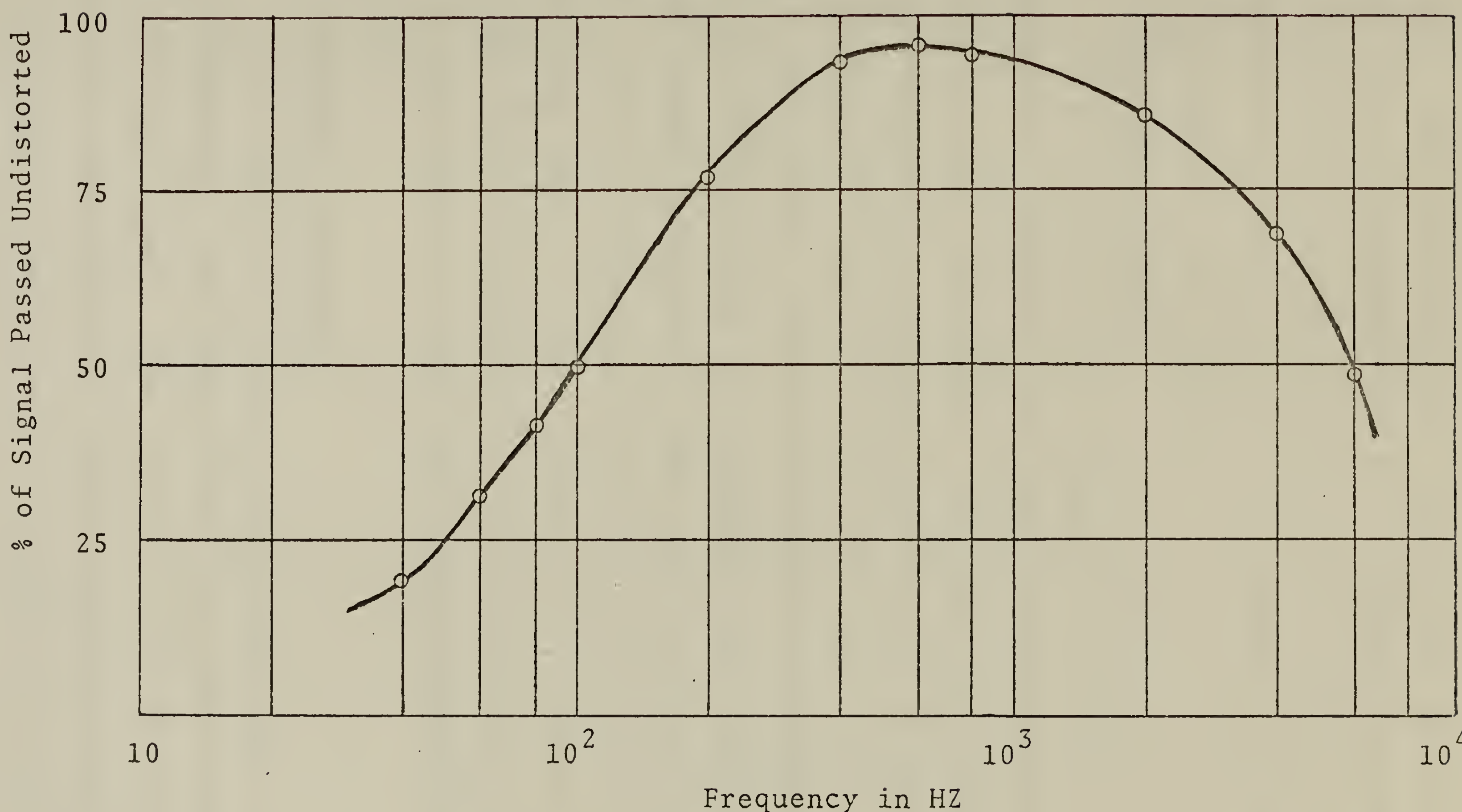


Figure 26: Frequency Response of System

With the fiber connected, a maximum noise level of 15 millivolts and a maximum signal of 300 millivolts with sinusoidal signal was observed. This yielded an rms signal-to-noise ratio of approximately 20:1. Without the fiber optic, the beam dissipated rapidly, and the system yielded a signal-to-noise ratio of up to 5:1, depending on distance between transmitter and receiver.

3. <u>Transmission Loss</u>

The fiber optic loss is rated at 1 db/meter. A test was conducted to determine what length of fiber could be used and still pass information. The fiber was disconnected from the receiver end and moved outward until the photodiode could no longer distinguish signal from noise. At approximately 6 cm distance, the ratio of photocurrent dropped by a ratio of 20:1 or 26 db. At 1 db/meter loss, this would indicate another 26 meters of fiber could be used in the system. This is believed to be a very conservative estimate. For the three meters of fiber actually used, there was no appreciable loss of transmission. It is believed at least 30 to 35 more meters of fiber could be used effectively in the system.

4. <u>Harmonic Distortion</u>

A wave analyzer was used to determine signal content of the fundamental, and second, third, and fourth harmonic of a 1 KHZ input signal. The test was conducted with the system at peak operation with the best possible output. Figure 27 shows the test results. Although the signal

content was 36% at the second harmonic, no distortion was discernable by listening.

Harmonic	Frequency (KHZ)	Signal Content (%)
Fundamental	1	100
Second	2	36
Third	3	7
Fourth	4	Less than 1

Figure 27: Harmonic Distortion Tests

III. CONCLUSIONS

The gallium arsenide injection laser can be used effectively for voice and other low data rate transmissions. Since the diode must be pulsed to operate, a pulse modulation scheme, and especially pulse position modulation is very easy to implement using integrated circuits. Compactness of size and portability may also be maintained.

The bandwidth objective of two kilohertz to pass a voice signal was easily met. With observable bandwidths of up to six kilohertz, future work could be directed toward suitable multiplex systems.

In a pulse-position-modulated optical system, beam coherence is not necessary. The system worked equally well in both LED and LASER modes. The laser puts out a sharper, more powerful pulse, and may increase the transmission distance at the expense of relatively slow pulse repetition frequency, higher power requirements, and overheating for an avalanche system. The LED mode can carry the same amount of information, requires less power to operate, and may be pulsed at much higher rates. The LED system is more efficient.

Although infrared wavelengths make gallium arsenide emissions relatively secure, collimation is difficult for use in line of sight work. With fiber optics, collimation is not necessary. As technology continues in the development of a low-loss fiber, longer distances will become

possible in addition to the numerous advantages of using fiber guides and light for communications.

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13. ABSTRACT

An optical communications system, suitable for simplex voice transmission is constructed, and demonstrated for straight line-of-sight, and for curved path operation using lenses and fiber optics. The system uses a pulsed gallium arsenide injection laser in the transmitter, operating at repetition frequency eight to fifteen kilohertz, and a p-i-n photodiode in the receiver. Pulse position modulation is used to transfer information as well as to trigger an avalanche transistor switch to drive the laser.

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